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EVALUATION OF H_2S-INDUCED STEPWISE CRACKING OF LINEPIPE

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EVALUATION OF H_2S-INDUCED STEPWISE CRACKING OF LINEPIPE

by

G.J. Biefer* and M.J. Fichera**

ABSTRACT

The results of evaluations of stepwise cracking susceptibility of nine gas transmission pipes are presented in order to record progress and serve as a basis for discussion.

ÉVALUATION DES TUYAUX DE CANALISATION QUANT À LEUR SUSCEPTIBILITÉ À LA FISSURATION EN GRADINS CAUSÉ PAR H_2S

par

G.J. Biefer* et M.J. Fichera**

RÉSUMÉ

On a fait l'évaluation de neuf tuyaux de canalisation de gaz, quant à leur susceptibilité à la fissuration en gradins. On donne les résultats des travaux pour enregistrer le progrès et pour susciter la discussion.

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INTRODUCTION

It has been observed since about 1950 that steel pipe exposed to wet, H_2S (sour) environments sometimes fails by cracking. For steel under tensile stress, such failures are of a brittle character and are often referred to as sulphide stress cracking (SSC). A related form of H_2S-induced damage that can occur in unstressed as well as stressed steel has often been termed stepwise cracking (SWC), because of the step-like appearance sometimes shown by crack profiles.

As part of project 425102 (FY 83-84) of the Energy Technology Activity of Energy, Mines and Resources Canada, the susceptibility to cracking of gas transmission linepipe in wet H_2S environments is being investigated at the Physical Metallurgy Research Laboratories (PMRL) of CANMET. A review of the available literature on the SWC of linepipe steel in sour environments has been published (1), and results obtained in tests of the SWC susceptibility of linepipe steels have been reported (2,3).

Susceptibility of steels to SWC has been evaluated primarily by the standard test method currently under development by the National Association of Corrosion Engineers (NACE) Task Group T-1F-20 (4). The proposed NACE Standard is based on a test previously developed by H.C. Cotton, then of British Petroleum, often called the "B.P. Test". In the proposed NACE Standard, rectangular coupons of steel are exposed to an H_2S environment, after which metallographic sections are prepared and examined optically for cracks.

The present report supplements and includes some of the earlier work at PMRL by presenting the detailed results with a minimum of interpretation for all standard SWC tests performed on the nine linepipe steels examined during the first phase of the research. Data obtained by auxiliary measurements are also included. Throughout, emphasis has been placed on an evaluation of experimental procedures.

EXPERIMENTAL

MATERIALS

Nine samples of commercial gas transmission linepipe - eight of Canadian manufacture - were procured by PMRL for this and other research. Table 1 provides a general description of the pipes. Mechanical and representative

impact properties are given in Table 2 and chemical compositions in Table 3. Rockwell macrohardness values were determined at PMRL and appear in Table 4.

Pipes AB and Z are examples of commercial practice during 1975-76 and were manufactured to Foothills Pipeline Limited Specification P100 (1975) for the Alaska Highway Pipeline Project. A comprehensive metallurgical evaluation of these pipes has been published (5).

Pipes AE, AG and CC were manufactured during 1979-80 for Arctic service and embody improvements in technology compared to AB and Z.

Pipes CA, CB and CD were also manufactured during 1979-80 and are typical products of this period. Pipe CA was designed for natural gas transmission in the U.S.A., while CB was designed for similar service in Canada. CD was manufactured for gas and liquid transportation pipelines not requiring specific notch toughness properties.

Pipe CE differs from the others in that it was manufactured in 1981 in Japan specifically for sour gas service.

Metallographic sections of the mill welds of each of the as-received pipes showed no sign of weld cold cracking or other internal damage. As part of the examinations, observations of typical inclusions near the weld were made, as shown in Table 5. Only pipes AB and CA exhibited distinctly elongated inclusions, that are known to be conducive to SWC (1); CD had ellipsoidal inclusions. Examples are shown in Fig. 1.

METHODS

The SWC test procedures used at PMRL were essentially those proposed by Bruno and Hill (4), and have been described in detail by M.J. Fichera (6).

In brief, three pieces of steel about 300 x 160 mm were removed from the pipes at specified locations with respect to the mill weld. The pieces were flattened and test coupons, 20 x 100 mm x the pipe wall thickness (less the small amount removed from the thickness during machining), were prepared as follows:

1. coupons with lengths transverse to the direction of the mill weld, and containing the weld at the centre;
2. coupons with lengths in the plate rolling direction, from parent metal approximately 90° around the pipe circumference from the mill weld;
3. coupons with lengths in the plate rolling direction, from parent metal approximately 180° around the pipe circumference from the mill weld.

The dry-ground coupons were degreased, weighed, and immersed for 4 days in an H_2S-saturated solution at a room temperature averaging about 25°C. Two test solutions were used; the synthetic seawater (B.P.) solution specified by T-1F-20 (initial pH 5.5) (4) and the NACE solution - 5% NaCl, 0.5% acetic acid (initial pH 2.9). The NACE solution is far more aggressive than the B.P. solution and is suitable for evaluating steels highly resistant to SWC. For each pipe, three coupons from each of the above three pipe locations were tested - usually simultaneously, in 5 L of solution (9.5 mL of solution/cm^2 of coupon area).

After coupons had been exposed to an H_2S environment, loosely adherent corrosion film was removed by scrubbing under running water. The clean, dried coupons, with small amounts of remaining corrosion film, were then re-weighed to determine the approximate corrosion rates shown in Table 6. At this stage, in accordance with the proposed NACE Standard, the coupon major surface corresponding with the pipe outer surface was photographed to record the amount of surface blistering.

Metallography

The amount of SWC was evaluated metallographically as follows:

Three metallographic sections normal to the plate rolling direction were prepared at specified locations in each coupon. The sections were ground, polished, etched, repolished, and examined for cracks using a microscope. The extent of the cracking was reported quantitatively using the method described in reference 4, and omitting the very few cracks found in the weld fusion zone. The values of the SWC ratios (CTR, CLR, and CSR; see Fig. 2) given for each coupon are the average of the three metallographic sections. In coupons containing the weld, the middle metallographic section includes the weld fusion zone, the weld heat-affected zone (HAZ), and some adjacent parent metal. The other two sections examined, one on each side of the weld, are 100% parent metal and are referred to as being about 0° around the pipe circumference from the weld.

Consideration of the SWC ratios in Fig. 2 reveals that the CLR, unlike the other two ratios, is a function of coupon thickness T. All else being equal, the CLR will increase with increasing T, and comparisons of SWC susceptibility, in terms of CLR, are only valid for coupons having the same thickness.

To eliminate the effect of coupon thickness, SWC crack length ratios may be expressed in terms of concentration per unit area, i.e.,

$$\%CLR/cm^2 = \Sigma \frac{\ell_i}{L} \; 100\%/TL \qquad \text{Eq 1}$$

Here, T is the test coupon thickness in cm and L = 2cm.

Diffusible hydrogen at 45°C

Prior to a metallographic examination for SWC, some of the coupons were tested for "diffusible hydrogen at 45°C". The methods used at PMRL have been described in detail by J.C. Selwyn (7). In brief, immediately after exposure to an H_2S environment, the coupon is cleaned, dried rapidly (without heating) and immersed in glycerol at 45°C under a gas collecting vessel. Hydrogen is evolved from the coupon. The volume collected in 3 days is measured and reported as mL (STP) H_2 per 100 g of coupon weight.

Ultrasonic C-scan

Many investigators have evaluated test coupons for SWC by means of ultrasonics (1). To demonstrate this approach, twenty-seven test coupons, representing the three standard locations for each of the nine pipes, were exposed for 4 days in H_2S-saturated synthetic seawater (B.P. solution). The coupons were then evaluated for SWC by Alcan personnel using the Sperry ultrasonic C-scan facility at Alcan International Limited, Kingston, Ontario (8).

In this evaluation, an ultrasonic beam scanned one of the coupon major surfaces, penetrating the through thickness direction with respect to the rolled plate. The discontinuities constituting SWC were detected and displayed as darkened areas in a 20 x 100 mm image of each coupon produced by a chart recorder.

The coupon images were analyzed at PMRL by M.T. Shehata and B.R. Casault of the Metallurgy Section of PMRL (9). A "Quantimet 900" image analyzing computer was used to determine the area percentage of SWC displayed in each coupon to an accuracy of ±10%.

RESULTS

PRELIMINARY TESTS

Effect of flattening pieces of pipe

Machining of SWC test coupons from linepipes is facilitated if the fairly large pieces cut from the curved pipe wall are first mechanically flattened. This procedure is permitted by the proposed NACE standard; however, the literature indicated that cold-working may have a significant effect upon SWC susceptibility (1).

Comparative SWC immersion tests were, therefore, performed in both the B.P. and NACE solutions on standard coupons from flattened pipe wall, and on specially prepared curved (non-flattened) coupons - all from pipe CA. The results, given in Table 7, showed that any effect of pipe wall flattening was less than the variability found within any group of similar coupons (2).

Orientation of metallographic section examined for SWC

In the proposed NACE Standard, the test coupon surfaces examined for SWC are always normal to the plate rolling direction. However, a few researchers examine a "longitudinal" plane, i.e., normal to the long transverse direction of the rolled plate.

For one of the SWC test coupons of pipe CA, both the standard and longitudinal planes were examined for cracks and evaluated in the usual way. The results, given in Table 8, are too scanty to be conclusive, but show that, in this specimen, less through-thickness cracking is seen in the non-standard longitudinal sections. There was, therefore, nothing to indicate that examination of the longitudinal sections would be preferable, and some suggestion that it would be a less sensitive means of detecting SWC.

SURFACE BLISTERING

After immersion in an H_2S environment, most of the coupons showed surface blisters of varying size and number, some cracked at the edges or across the diameter; examples of "blistered" and "slightly blistered" coupons are shown in Fig. 3. General trends in the blistering are presented qualitatively in Table 9. It was also observed that coupon sides (i.e., longitudinal through-thickness planes) usually exhibited surface cracks in the rolling

plane, sometimes showing a stepped configuration. The position of these surface cracks in the coupon thickness showed good qualitative agreement with metallographic determinations, reported below, of the percentage of SWC which was "central" and "surface" (Fig. 2).

METALLOGRAPHY

SWC ratios

The SWC ratios for each coupon evaluated are given in Tables 10-27. According to the requirements of the proposed NACE SWC test method, ratios are also reported for each of the three metallographic sections examined in each coupon.

Tables 28-30 list the CTR, CLR, and CSR ratios obtained for each pipe when the results for the three coupons measured at each pipe location are averaged. In most cases, the ratios are rounded off to two significant figures.

SWC data on weld coupons were analyzed to obtain SWC ratios on parent metal about 0° from the weld (6 metallographic sections) and in weld HAZ metal (parts of three middle metallographic sections). Average SWC ratios thus obtained in tests in synthetic seawater are given in Table 31, while those from tests in the NACE solution are given in Table 32.

Depth of SWC

As reported previously, in each pipe SWC showed a characteristic and non-uniform distribution through the wall thickness (2,3). This observation was quantified for the six parent metal coupons tested from each pipe by determining the percentage of CSR crack groups in the zones illustrated in Fig. 2:

1. "central" (between 1/4 and 3/4 through the wall thickness); and
2. "surface" (within 1/4 of the thickness from the wall surface).

The results appear in Table 33, and in most cases show good general agreement between the two test solutions. However, valid distributions could not be calculated for CD and CE where there were few or no cracks. CC exhibits the nearest approach to an even distribution of SWC across the wall thickness.

Sulphide stress cracking

Unexpectedly, what appeared to be SSC was observed in metallographic sections of some of the weld coupons, as indicated in Tables 31 and 32. These cracks, and the very few observed in the weld fusion zone, were not measured in the usual way and did not contribute to the SWC ratios reported.

A 4 mm long apparent SSC crack in the coarse-grained HAZ of coupon Z-1W has been reported previously (2,3). Coupons AE-2W and AG-2W also exhibited what appeared to be SSC in the coarse-grained HAZ, and examples of short cracks propagating from one of the coupon major surfaces are shown in Fig. 4. Only after the metallographic section of AG-2W had been etched and repolished a second time was it observed that there were also fine SSC cracks originating on the face of the weld fusion zone. Coupon CC-6W exhibited apparent SSC in the central part of the weld, as shown in Fig. 5.

Microhardness measurements

Subsequent to the detection of apparent SSC, microhardness traverses were made across the weld HAZ on coupons from all nine pipes, using a Tukon tester with a Knoop diamond penetrator and a 500 g load. For pipes AE, AG and Z the traverses were performed on the coupons which had shown indications of SSC.

The results are given in converted Rockwell hardness units in Table 34. Pipes AE, AG and Z show numerous hardness values well above HRC 22 - the upper hardness limit recommended by NACE for minimizing SSC in carbon and most low alloy steels in sour service (10). In each of these three pipes, the highest hardnesses occurred in the weld HAZ. In the other six pipes, only one measurement above HRC 22 was recorded.

DIFFUSIBLE HYDROGEN AT 45°C

Results obtained in these measurements are given in Table 35, in each case accompanied by the CTR ratio determined metallographically on the same test coupon. For parent metal coupons tested in the two solutions, Fig. 6 shows hydrogen content plotted against CTR. For each pipe, a linear relationship is shown.

In Fig. 7, hydrogen contents of all coupons in Table 35 are similarly plotted against CTR values.

ULTRASONIC C-SCAN

An examination by ultrasonic C-scan yielded the chart recorder images of test coupons which are reproduced in Fig. 8-10 (8). Here, the well-defined dark areas represent probable SWC while the less clearly-defined arrays of fine lines have no technical significance. The white areas correspond to SWC-free regions. In Table 36, the percentage of each coupon image covered by SWC, as measured by the Quantimet 900, is given (9).

Pipe CD had shown no SWC in metallographic evaluations following exposure to H_2S-saturated synthetic seawater (B.P. test). The identical L-shaped markings in all three coupons, which even traversed the SWC-immune weld zone in CD-W, were therefore assumed to be artifacts. This was confirmed by manual measurements with an ultrasonic probe at PMRL, and the correct values of SWC for CD coupons were taken as <1%.

In coupon AG-180, the largest rod-like marking had an artificial appearance, but ultrasonic measurements at PMRL showed that it represented an actual discontinuity.

DISCUSSION

SURFACE BLISTERING

Examination of coupon surfaces after exposure to H_2S environment showed some correlation with SWC behaviour from metallography, as indicated below:

1. Pipes showing very little SWC, such as CD and CE, showed almost no external blisters. But CB and Z, showing significant SWC concentrated in the central part of the wall thickness, appeared not much more blistered than CD and CE. AE and AG, on the other hand, showed copious surface blistering even though SWC was predominantly in the central part of the wall thickness. Caution must, therefore, be exercised in interpreting the significance of external blistering, or its absence.

2. As noted previously, the position of the straight (or stepped) surface cracks on the coupon sides indicated correctly whether predominantly "surface" or the less deleterious "central" SWC might be expected.

METALLOGRAPHY

SWC ratios

As pointed out previously (3) and confirmed by the ultrasonic C-scan results, SWC crack areas are unevenly distributed in the pipe, are irregular in shape, and relatively few in number. Because of this, the SWC data of Tables 10-27 show instances of relatively poor agreement among the three metallographic sections in each coupon, and among the three replicate coupons tested at each of the three pipe locations. Nevertheless, though extremely time-consuming, metallographic evaluations at least provide incontravertible evidence of SWC, unlike the nondestructive methods considered. Differences among the pipes were significant, and showed the following main trends:

1. Pipes CD and CE were significantly more resistant to SWC than the other 7 pipes. They were very nearly immune to cracking in tests in synthetic seawater and only cracked to a minor extent in the NACE solution. CE was more resistant than CD.

2. In the aggressive NACE solution, pipes AB, AE, AG, CA, CB, CC and Z were all susceptible to SWC and exhibited no significant differences in behaviour with the possible exception of Z, which was fairly resistant near the weld.

3. In the less aggressive synthetic seawater (B.P.) solution, the above 7 pipes showed differences in susceptibility to SWC as follows:
   (i) Near the weld, pipes CB, CC and Z (neglecting its single large apparent SSC crack) were resistant to SWC while AB, AE, AG and CA were susceptible;
   (ii) In parent metal away from the weld, pipes AB, AG and CC were resistant to SWC while AE, CA, CB and Z were susceptible. Only pipe CC was resistant to SWC both near the weld and away from it.

As discussed previously (2,3), in ingot-cast steels maximum susceptibility to SWC would be expected at locations 180° from the weld, i.e., in plate most nearly corresponding to the ingot core (11). Conversely, parent metal near the weld would be expected to show the highest resistance to SWC. The 7 SWC-susceptible steels had been ingot-cast; in tests in synthetic

seawater, in which significant differences were observable, pipes AE, CA, CB, CC, and Z on the whole exhibited this behaviour. Pipes AB and AG, on the other hand, clearly showed their maximum susceptibility to SWC near the weld. The positioning of the most SWC-susceptible metal adjacent to the weld must result from details of steelmaking and pipe manufacturing methods, not known to the writers.

Depth of SWC

The distribution of SWC across the pipe wall thickness is also a significant factor, as discussed previously (3). For pipes containing a sour environment, maximum susceptibility to SWC at the centre of the wall thickness is considered to be less deleterious than maximum susceptibility to SWC at the surface. In the former case the most SWC-resistant metal on the inner pipe surface will be in contact with the H_2S environment, while, because the hydrogen can escape at the outer surface the decreasing concentration of dissolved hydrogen through the wall thickness will impose only intermediate hydrogen concentrations on the most SWC-susceptible central zone of the plate (12). In the present research, only pipes AB and CA showed maximum susceptibility to SWC at the surface (Table 33).

Sulphide stress cracking

The occurrence of apparent SSC in the unstressed test coupons was unexpected. But the characteristics of the crack profiles and the tendency of SSC to occur in steels showing hardnesses above HRC 22 provided supporting evidence. Presumably, localized tensile residual stresses introduced by the pipe-flattening operation were present.

DIFFUSIBLE HYDROGEN AT 45°C

While a number of researchers have reported a correlation between the amount of diffusible hydrogen evolved at 45°C and SWC evaluated in some other way, others have failed to find any such correlation (1).

The linear relationships between hydrogen content and CTR, shown in Fig. 6 for 4 of the pipes, indicate that the determination of diffusible hydrogen at 45°C might provide a useful index of the amount of SWC in tests on the same steel exposed to different H_2S environments. In particular, this method might be used to determine C_{TH}, the threshold hydrogen concentration

at which SWC occurs in a given steel (13). Advantages of the method are its simplicity, nondestructiveness, low cost, and relatively low demand on operator time.

However, each of the pipes, as shown in Fig. 6, generated a different curve. Therefore, there is no general relationship, for all steels, between diffusible hydrogen content and the amount of SWC. This is evident from a study of Fig. 7, which shows all the data of Table 35.

ULTRASONIC C-SCAN

The % coverage by SWC obtained from the ultrasonic evaluation of coupons given the B.P. test was related to $\%CLR/cm^2$ (Eq 1) as shown in Fig. 11. As expected, there was considerable scatter, but the C-scan rapidly distinguishes between resistant and susceptible steels and identifies the location and the shape of SWC-damaged areas. However, a few results were anomalous and required verification. Blanchard and Sourdillon have described an inexpensive manual ultrasonic method for evaluating SWC damage (14).

GENERAL

Elongated inclusions have been shown to provide more favourable sites for the initiation of SWC than globular inclusions (1). In the present research, distinctly elongated inclusions were only observed in pipes AB and CA (Fig. 1). Inclusions in CD, also shown in this figure, were of the ellipsoidal type observed in semi-killed steels shown to be highly resistant to SWC by Moore and Warga (15). Pipes AB and CA showed no obvious detrimental effect of inclusion shape, and were not notably inferior to the others in the group of 7 SWC-susceptible pipes. A detailed characterization of the inclusions is needed.

CD is an inexpensive, hot-rolled, semi-killed steel with high sulphur and carbon contents and no inclusion shape control, not intended for use in pipelines requiring specific notch toughness properties. Yet it showed distinctly better resistance to SWC than several high-performance Arctic pipes and was in fact comparable to CE, which had been specially designed for sour service.

Measurements of diffusible hydrogen at 45°C showed that pipe CD absorbed more hydrogen than CE, at the same SWC damage level (Fig. 6). This may indicate that, while CE's superior performance is due to an elimination

of cracking sites, CD benefits from the presence of a large number of "benign" traps - not generating cracks - in which hydrogen is harmlessly absorbed.

Further comparative studies of the SWC behaviour of pipes CD and CE might be instructive.

SUMMARY

The most important results are summarized below:

1. Nine gas transmission linepipes (Grades 290-483) were evaluated for susceptibility to SWC, using the metallographic method of the SWC Standard under development by NACE Task Group T-1F-20. Measurements in triplicate showed that only fair reproducibility could be expected.

2. Metallographic evaluations of SWC were performed on coupons that had been exposed to one of two H_2S-saturated solutions, synthetic seawater (B.P.) or the more aggressive NACE (0.5% acetic acid, 5% sodium chloride). Pipes CD and CE were virtually immune to SWC in the B.P. solution and only slightly attacked in the NACE solution. The other 7 pipes showed significant differences in resistance to SWC after exposure to the B.P. solution, but were not significantly resistant in the NACE solution.

3. In measurements of "diffusible hydrogen at 45°C", parent metal coupons showed increased hydrogen absorption with increased SWC determined metallographically. However the data points for each pipe were described by a different curve; meaning that absorbed hydrogen cannot be used as a general index of SWC. However, the method should be useful for a particular alloy exposed to different H_2S environments, e.g., in determining C_{TH}, the threshold hydrogen content for SWC.

4. Evaluation of SWC in test coupons by means of an ultrasonic C-scan was shown to be a rapid and effective method. However, occasional false positives may be recorded which require further investigation.

FUTURE WORK

Measurements of the effects of stress and of temperature on SWC are underway. Measurements of C_{TH}, the threshold hydrogen content for SWC, are planned. Equipment will be designed and constructed to enable studies of the relationship between SWC and hydrogen permeation flux.

For the nine pipes in the research program, a Quantimet 900 image analysing computer is being used to characterize the inclusions, which are believed to provide the most favourable sites for the generation of SWC. These findings will be related to known SWC behaviour of the pipes.

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Table 1. Linepipes used in SWC research.

Pipe	Size (diam x wall thickness)	Grade MPa(ksi)	Notes
AB	1067 x 13.7 mm	483 (x70)	semi-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
AE	1219 x 13.7 mm	483 (x70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
AG	914 x 13.7 mm	483 (x70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
CA	610 x 13.5 mm	359 (x52)	fully-killed, ingot-cast, controlled-rolled, longitudinal sub-arc welded
CB	762 x 11.7 mm	448 (x65)	fully-killed, ingot-cast, controlled-rolled, longitudinal sub-arc welded
CC	1219 x 13.7 mm	483 (x70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded
CD	508 x 9.53 mm	290 (x42)	semi-killed, ingot-cast, hot rolled, longitudinal sub-arc welded
CE	864 x 15.9 mm	359 (x52)	fully-killed, continuous cast, controlled-rolled, longitudinal sub-arc welded
Z	1067 x 13.7 mm	483 (x70)	fully-killed, ingot-cast, controlled-rolled, spiral sub-arc welded

Table 2. Mechanical and impact properties provided by manufacturers.

Code	Yield strength MPa	Ultimate tensile strength MPa	Elong. %	Impact properties (body)
AB body	516	639	36	DWTT @ -18°C
weld	-	696	-	6504 J
				100% shear
AE body	574	762	33	DWTT @ -4°C
weld	684	796	20	4813 J
				100% shear
				Charpy @ -4°C
				125 J
				99% shear
AG body	524	645	36	DWTT @ -20°C
				5934 J
				87% shear
				Charpy @ -20°C
				214 J
				100% shear
CA body	417	514	38	DWTT @ 0°C
weld	-	552	-	2298 J
				98% shear
				Charpy @ 0°C (2/3 size):
				26 J
				94% shear
CB body	470	576	38	DWTT @ -5°C
weld	-	599	-	1085 J
				50% shear
				Charpy @ -5°C (2/3 size):
				31 J
				98% shear

Table 2 (cont'd)

Code	Yield strength MPa	Ultimate tensile strength MPa	Elong. %	Impact properties (body)
CC body	493	635	40	DWTT @ -4°C 5627 J 100% shear Charpy @ -4°C 117 J 94% shear
CD body weld	397 -	516 544	31 -	-
CE body weld	383 410	471 504	46 31	DWTT @ -20°C 100% shear Charpy @ -20°C 298 J
Z body weld	503 -	633 749	39 -	DWTT @ -18°C 5694 J 90% shear Charpy @ -18°C 115 J 96% shear

Table 3. Analysis of linepipes provided by manufacturer.

Element	AB	AE	AG	CA	CB	CC	CD	CE	Z
C	0.06	0.08	0.08	0.13	0.12	0.60	0.22	0.068	0.049
Mn	1.80	1.98	1.70	1.17	1.48	1.76	0.85	0.86	1.94
P	0.009	0.011	0.014	0.005	0.011	0.004	0.004	0.006	0.007
S	0.017	0.005	0.004	0.016	0.010	0.006	0.028	0.001	0.011
Si	0.02	0.29	0.15	0.27	0.27	0.25	0.06	0.256	0.28
Nb	0.058	0.045	0.072	0.015	0.038	-	-	0.020	0.060
Sn	0.02	0.005	0.015	-	0.002	-	-	-	-
Cu	0.22	0.053	0.23	-	0.029	0.028	-	-	-
Ni	0.11	0.033	0.20	-	0.012	0.009	-	0.37	-
Cr	0.04	0.097	0.09	-	0.057	0.044	-	-	-
Mo	0.27	0.24	0.21	-	0.007	0.212	-	-	0.489
V	-	0.05	-	-	0.040	0.035	-	-	-
Al	-	0.017(1)	-	-	0.024(1)	0.034(1)	-	0.024(2)	-
Ca	-	-	-	-	-	-	-	0.0037	-
O	-	-	-	-	-	-	-	0.0025	-
N	-	-	-	-	-	-	-	0.0038	-
C/E	0.44(3)	0.47	0.45(3)	0.33	0.37	0.40	0.36	0.24	0.37

(1) acid-soluble

(2) total

(3) calculated by: $C/E = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

Table 4. Rockwell macrohardness of pipes used in SWC measurements.

Pipe	Parent[1]		Weld heat-affected zone		Weld fusion zone	
	Av hardness HRB	No. of determinations	Av hardness HRB	No. of determinations	Av hardness HRB	No. of determinations
AB	93.2	21	93	3	97	3
AE	96.3	21	98[2]	3	97.5	3
AG	95.2	21	95	3	97	3
CA	85.1	21	86	3	90.5	3
CB	90.9	21	91.5	3	94.5	3
CC	91.5	21	94	3	97	3
CD	85.8	21	83.5	3	83	3
CE	78.9	21	82	3	93	3
Z	92.4	21	95	3	98[2]	4

[1] Determined at locations adjacent to the weld, and 90° and 180° around the pipe circumference from the weld.

[2] This is also equal to HRC 20.5.

Table 5. Typical inclusions near mill welds of pipes.

Pipe	Length or Diam um	Description
AB	40-100	Many, elongated
AE	15-25	Few, globular
AG	10-30	Many, globular
CA	110-330	Many, elongated
CB	7-11	Very few, globular
CC	15-25	Many, globular
CD	15-25	Few, slightly elongated
CE	10-20	Very few, globular
Z	5-10	Very few, globular

Table 6. Corrosion rates in 4-day immersions in H_2S-saturated solution at about 25°C.

Pipe	Corrosion rate, µm/a			
	Synthetic seawater (B.P. solution)*		0.5% acetic acid, 5% NaCl (NACE solution)**	
	Parent	Weld	Parent	Weld
AB	360	400	1000	1020
AE	430	430	790	790
AG	340	400	940	950
CA	330	350	730	660
CB	400	310	700	690
CC	330	350	1000	940
CD	270	300	910	880
CE	130	120	650	870
Z	480	450	660	780

*Final pH: 4.9-5.1

**Final pH: 3.3-3.6

Table 7. Effect of flattening curved pipe wall on SWC shown by machined weld coupons from pipe CA.

Test solution	Shape	Coupon	SWC ratios, %		
			CTR	CLR	CSR
B.P.	curved	CA-1W	2.9	10	0.33
		CA-5W	4.0	27	0.52
		CA-10W	0.7	9.3	0.10
		Av	2.5	15	0.32
B.P.	flattened	CA-15W	8	27	0.77
		CA-19W	2.3	17	0.08
		CA-24W	4.7	16	0.22
		Av	5.0	20	0.36
NACE	curved	CA-2W	27	65	4.86
		CA-6W	17	65	5.19
		CA-11W	18	63	2.72
		Av	21	64	4.26
NACE	flattened	CA-16W	17	52	2.31
		CA-20W	19	58	2.55
		CA-25W	23	78	2.99
		Av	20	63	2.62

Table 8. Effect of metallographic plane examined in parent metal SWC coupon CA-49 after testing in NACE solution.

Plane examined	Metallographic section	SWC ratios, %		
		CTR	CLR	CSR
Standard (normal to plate rolling direction)	1	36.5	75.6	8.16
	2	8.7	26.6	0.49
	3	31	97	5.63
	Av	25(18)*	66(48)*	4.76(2.8)*
Longitudinal (normal to long transverse direction in plate)	1	6.2	30.8	0.56
	2	5.8	35.9	0.46
	3	4.6	65.8	1.21
	Av	5.5	44	0.74

*Average SWC ratios from three parent (90° from weld) coupons, including CA-49, obtained in standard SWC tests.

Table 9. Blistering on coupon major surfaces after 4-day immersion in H_2S-saturated solution at R.T.

Pipe	Synthetic seawater (B.P.)					Acidified NaCl solution (NACE)				
	W[4]	HAZ[5]	P-0[6]	P-90[7]	P-180[8]	W	HAZ	P-0	P-90	P-180
AB	0[1]	B[3]	B	SB[2]	SB	0	B	B	B	B
AE	0	0	B	SB	SB	0	SB	B	B	B
AG	0	B	B	SB	SB	0	SB	B	B	B
CA	0	SB	B	B	B	0	B	B	B	B
CB	0	0	0	0	B	0	0	SB	SB	SB
CC	0	0	SB	SB	B	0	SB	B	B	B
CD	0	0	0	0	0	0	0	0	SB	0
CE	0	0	0	0	0	0	0	0	0	SB
Z	0	0	0	SB	0	0	0	0	0	0

(1) 0 = No blisters
(2) SB = Slightly blistered
(3) B = Blistered
(4) W = Weld
(5) HAZ = Weld heat-affected zone
(6) P-0 = Parent metal, 0° from weld
(7) P-90 = Parent metal, 90° from weld
(8) P-180 = Parent metal, 180° from weld

Table 10. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe AB.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
AB-1W	Across weld	1	2.6	2.1	0.05
		2	1.5	4.6	0.02
		3	14.2	55.8	2.63
		Av	6.1	20.8	0.90
AB-5W	Across weld	1	0	0	0
		2	4.6	13.1	0.17
		3	10.9	66.3	1.81
		Av	5.2	26.5	0.66
AB-10W	Across weld	1	0	0	0
		2	5.0	18.4	0.08
		3	3.5	9.1	0.32
		Av	2.9	9.2	0.13
AB-26	Parent, 90° from weld	1	5.0	9.5	0.48
		2	7.2	8.8	0.63
		3	0	0	0
		Av	4.1	6.1	0.37
AB-34	Parent, 90° from weld	1	0	0	0
		2	0.8	2.5	0.02
		3	0	0	0
		Av	0.3	0.8	0.01
AB-42	Parent, 90° from weld	1	4.0	12.2	0.39
		2	0	0	0
		3	4.4	15.9	0.43
		Av	2.8	9.4	0.27
AB-51	Parent, 180° from weld	1	12.0	27.6	1.49
		2	0	0	0
		3	2	7.3	0.14
		Av	4.6	11.6	0.55
AB-59	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
AB-67	Parent, 180° from weld	1	0	0	0
		2	4.4	13.3	0.59
		3	2.8	14.9	0.42
		Av	2.4	9.4	0.33

Table 11. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe AE.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
AE-1W	Across weld	1	1.6	29.8	0.13
		2	2.8	1.4	0.04
		3	8.6	23.1	0.90
		Av	4.3	18.1	0.36
AE-5W	Across weld	1	7.1	32.0	1.12
		2	1.2	17.2	0.21
		3	5.9	31.7	0.67
		Av	4.7	26.9	0.67
AE-10W	Across weld	1	0.4	0.7	<0.01
		2	3.6	11.9	0.18
		3	13.5	69.8	2.21
		Av	5.8	27.5	0.80
AE-26	Parent, 90° from weld	1	2.5	33.2	0.20
		2	3.4	66.2	0.19
		3	12.5	98.3	3.07
		Av	6.1	65.9	1.15
AE-34	Parent, 90° from weld	1	10.5	76.3	1.85
		2	5.0	38.1	0.40
		3	15.9	87.3	2.86
		Av	10.5	67.2	1.70
AE-42	Parent, 90° from weld	1	10.5	40.3	1.29
		2	5.5	62.9	1.72
		3	8.3	62.0	1.87
		Av	8.1	55.1	1.63
AE-51	Parent, 180° from weld	1	15.3	127.8	4.83
		2	7.1	33.7	2.40
		3	2.1	40.3	0.39
		Av	8.2	67.3	2.54
AE-59	Parent, 180° from weld	1	3.3	10.3	0.25
		2	2.9	77.5	0.68
		3	13.9	104.2	3.32
		Av	6.7	64.0	1.42
AE-67	Parent, 180° from weld	1	7.2	91.9	4.01
		2	8.9	86.6	4.32
		3	6.8	66.2	0.91
		Av	7.6	81.6	3.08

Table 12. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe AG.

Coupon No.	Location in pipe	Section No.	% CTR	% CLR	% CSR
AG-1W	Across weld	1	16.8	58.9	1.71
		2	2.8	5.9	0.17
		3	1.6	9.4	0.15
		Av	7.1	24.7	0.68
AG-5W	Across weld	1	8.3	52.1	1.01
		2	14.3	18.6	1.02
		3	0	0	0
		Av	7.5	23.5	0.68
AG-10W	Across weld	1	18.0	78.7	2.67
		2	0.4	3.6	0.01
		3	0.8	3.0	0.01
		Av	6.4	28.4	0.87
AG-26	Parent, 90° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
AG-34	Parent, 90° from weld	1	0	0	0
		2	0	0	0
		3	0.8	4.9	0.04
		Av	0.3	1.6	0.01
AG-42	Parent, 90° from weld	1	0.4	1.0	<0.01
		2	0	0	0
		3	0	0	0
		Av	0.1	0.3	<0.01
AG-51	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
AG-59	Parent, 180° from weld	1	0.4	0.7	<0.01
		2	1.9	2.0	0.04
		3	0	0	0
		Av	0.8	0.9	0.01
AG-67	Parent, 180° from weld	1	3.8	27.7	1.05
		2	0.4	1.0	<0.01
		3	0	0	0
		Av	1.4	9.6	0.35

Table 13. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe CA.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CA-15W	Across weld	1	5.2	19.3	0.26
		2	8.0	20.2	0.63
		3	10.9	42.4	1.42
		Av	8.0	27.3	0.77
CA-19W	Across weld	1	5.2	24.5	0.15
		2	0	0	0
		3	1.6	25.1	0.10
		Av	2.3	16.5	0.08
CA-24W	Across weld	1	7.6	17.3	0.43
		2	0.8	4.7	0.02
		3	5.6	27.3	0.20
		Av	4.7	16.5	0.22
CA-26	Parent, 90° from weld	1	6.8	31.8	1.08
		2	1.6	8.3	0.14
		3	18.4	45.0	4.02
		Av	8.9	28.4	1.75
CA-34	Parent, 90° from weld	1	0	0	0
		2	3.5	3.8	0.13
		3	8.7	40.3	1.25
		Av	4.1	14.7	0.46
CA-42	Parent, 90° from weld	1	10.2	50.5	3.50
		2	12.2	53.8	1.44
		3	0	0	0
		Av	7.5	34.8	1.65
CA-51	Parent, 180° from weld	1	4.4	24.4	0.57
		2	8.4	22.4	0.58
		3	15.0	57.9	3.71
		Av	9.3	34.9	1.62
CA-59	Parent, 180° from weld	1	8.7	48.9	0.76
		2	1.2	3.7	0.04
		3	11.0	22.1	0.82
		Av	6.9	24.9	0.54
CA-67	Parent, 180° from weld	1	19.4	64.8	3.07
		2	16.6	48.1	1.30
		3	31.6	68.9	4.95
		Av	22.5	60.6	3.11

Table 14. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe CB.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CB-1W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CB-5W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CB-10W	Across weld	1	6.5	7.8	0.50
		2	0	0	0
		3	1.6	4.3	0.07
		Av	2.7	4.0	0.19
CB-26	Parent, 90° from weld	1	11.0	38.8	2.48
		2	0.5	13.6	0.06
		3	3.1	23.1	0.72
		Av	4.9	25.2	1.09
CB-34	Parent, 90° from weld	1	6.4	42.6	1.67
		2	18.9	70.5	5.88
		3	11.9	34.5	2.25
		Av	12.4	49.2	3.27
CB-42	Parent, 90° from weld	1	25.0	114.6	9.45
		2	4.6	41.8	1.58
		3	6.3	24.9	1.03
		Av	12.0	60.4	4.02
CB-51	Parent, 180° from weld	1	8.9	77.0	4.23
		2	4.9	61.1	0.54
		3	27.6	166.8	8.71
		Av	13.8	101.6	4.49
CB-59	Parent, 180° from weld	1	7.7	63.7	1.46
		2	22.0	108.0	6.72
		3	16.9	78.9	2.79
		Av	15.5	83.5	3.66
CB-67	Parent, 180° from weld	1	22.4	90.6	6.75
		2	23.8	52.4	3.73
		3	19.2	63.2	6.82
		Av	21.8	68.7	5.77

Table 15. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe CC.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CC-1W	Across weld	1	0	0	0
		2	0	0	0
		3	0.8	10.8	0.09
		Av	0.3	3.6	0.03
CC-5W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CC-10W	Across weld	1	0	0	0
		2	0	0	0
		3	1.2	22.2	0.27
		Av	0.4	7.4	0.09
CC-26	Parent, 90° from weld	1	0.8	2.7	0.01
		2	1.6	5.5	0.04
		3	0	0	0
		Av	0.8	2.8	0.02
CC-34	Parent, 90° from weld	1	0	0	0
		2	3.2	12.6	0.06
		3	1.6	4.8	0.01
		Av	1.6	5.8	0.03
CC-42	Parent, 90° from weld	1	2.4	6.5	0.07
		2	2.8	8.8	0.18
		3	3.6	11.3	0.20
		Av	2.9	8.8	0.15
CC-51	Parent, 180° from weld	1	1.2	6.5	0.08
		2	9.1	32.4	0.35
		3	0	0	0
		Av	3.4	13.0	0.14
CC-59	Parent, 180° from weld	1	3.6	15.2	0.29
		2	2.8	43.2	0.64
		3	3.2	40.8	0.79
		Av	3.2	33.1	0.57
CC-67	Parent, 180° from weld	1	2.0	15.0	0.06
		2	3.2	22.1	0.24
		3	2.4	11.0	0.09
		Av	2.5	16.0	0.13

Table 16. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe CD.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CD-1W	Across weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-5W	Across weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-10W	Across weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-26	Parent, 90° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-34	Parent, 90° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-42	Parent, 90° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-51	Parent, 180° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-59	Parent, 180° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0
CD-67	Parent, 180° from weld	1 2 3 Av	0 0 0 0	0 0 0 0	0 0 0 0

Table 17. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe CE.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CE-1W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-5W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-10W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-26	Parent, 90° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-34	Parent, 90° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-42	Parent, 90° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-51	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	2.2	11.0	0.24
		Av	0.7	3.7	0.08
CE-59	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-67	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0

Table 18. SWC ratios in tests in H_2S-saturated synthetic seawater (B.P. solution) on pipe Z.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
Z-1W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
Z-5W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
Z-10W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
Z-26	Parent, 90° from weld	1	7.5	35.2	0.63
		2	3.6	31.7	0.39
		3	6.5	24.5	1.09
		Av	5.9	30.4	0.70
Z-34	Parent, 90° from weld	1	7.2	48.7	0.74
		2	8.1	34.9	1.08
		3	2.0	13.5	0.16
		Av	5.8	32.4	0.66
Z-42	Parent, 90° from weld	1	4.0	16.8	0.18
		2	2.0	14.5	0.29
		3	6.9	54.5	1.09
		Av	4.3	28.6	0.52
Z-51	Parent, 180° from weld	1	14.5	58.7	4.52
		2	4.0	15.2	0.39
		3	5.6	45.7	0.63
		Av	8.1	39.9	1.85
Z-59	Parent, 180° from weld	1	1.6	28.0	0.11
		2	4.4	48.2	0.69
		3	3.6	26.3	0.31
		Av	3.2	34.2	0.37
Z-67	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0.8	14.9	0.06
		Av	0.3	5.0	0.02

Table 19. SWC ratios in tests in H_2S-saturated NACE solution on pipe AB.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
AB-2W	Across weld	1	33.5	135.9	7.59
		2	22.3	61.0	2.46
		3	26.9	61.5	5.08
		Av	27.5	86.1	5.05
AB-6W	Across weld	1	20.8	73.3	3.62
		2	31.9	71.6	6.26
		3	23.3	49.3	3.92
		Av	25.3	64.7	4.60
AB-11W	Across weld	1	19.6	59.6	2.20
		2	9.8	30.4	0.98
		3	26.1	72.4	5.20
		Av	18.5	54.1	2.79
AB-27	Parent, 90° from weld	1	37.4	89.9	6.08
		2	28.9	95.1	8.14
		3	21.0	71.1	3.87
		Av	29.1	85.3	6.03
AB-35	Parent, 90° from weld	1	27.2	83.5	5.43
		2	18.6	43.8	2.00
		3	16.1	60.2	3.86
		Av	20.6	62.5	3.76
AB-43	Parent, 90° from weld	1	33.5	88.5	5.65
		2	14.2	71.8	1.92
		3	13.6	34.9	1.32
		Av	20.4	65.0	2.96
AB-52	Parent, 180° from weld	1	16.7	67.4	1.76
		2	23.9	63.4	4.74
		3	38.7	101.0	4.19
		Av	26.4	77.3	3.56
AB-60	Parent, 180° from weld	1	16.5	44.5	2.22
		2	18.8	38.8	1.64
		3	21.9	77.1	3.22
		Av	19.1	53.5	2.36
AB-68	Parent, 180° from weld	1	21.4	76.3	2.70
		2	17.9	47.4	1.53
		3	8.7	21.1	0.68
		Av	16.0	48.3	1.64

Table 20. SWC ratios in tests in H_2S-saturated NACE solution on pipe AE.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
AE-2W	Across weld	1	14.5	118.8	2.31
		2	15.7	47.3	2.80
		3	12.8	64.0	1.37
		Av	14.3	76.0	2.16
AE-6W	Across weld	1	18.3	63.4	2.63
		2	0.4	1.8	0.01
		3	10.6	37.2	1.15
		Av	9.8	34.1	1.26
AE-11W	Across weld	1	12.0	80.5	1.60
		2	16.8	17.7	2.97
		3	3.8	17.8	0.26
		Av	10.9	38.6	1.61
AE-27	Parent, 90° from weld	1	27.2	134.1	9.69
		2	12.7	90.5	3.52
		3	14.2	119.0	3.24
		Av	18.1	114.5	5.48
AE-35	Parent, 90° from weld	1	18.2	129.7	7.74
		2	13.8	137.8	2.73
		3	27.9	178.9	8.26
		Av	20.0	148.9	6.24
AE-43	Parent, 90° from weld	1	15.6	167.8	3.22
		2	14.3	131.9	5.73
		3	25.2	116.5	11.15
		Av	18.4	138.7	6.70
AE-52	Parent, 180° from weld	1	8.9	85.9	0.72
		2	17.1	137.9	2.63
		3	18.9	210.8	3.59
		Av	15.0	144.9	2.31
AE-60	Parent, 180° from weld	1	24.8	171.4	9.27
		2	18.6	158.5	3.66
		3	10.2	144.6	2.27
		Av	17.8	158.2	5.07
AE-68	Parent, 180° from weld	1	15.7	170.6	4.20
		2	5.5	55.6	0.80
		3	4.2	57.6	1.59
		Av	8.5	94.6	2.20

Table 21. SWC ratios in tests in H_2S-saturated NACE solution on pipe AG.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
AG-2W	Across weld	1	13.1	90.6	3.84
		2	7.2	24.5	0.99
		3	7.3	50.5	0.99
		Av	9.2	55.2	1.94
AG-6W	Across weld	1	17.4	142.0	3.77
		2	20.7	41.5	1.71
		3	21.0	75.8	4.24
		Av	19.7	86.4	3.24
AG-11W	Across weld	1	26.2	119.9	4.28
		2	3.2	14.1	0.38
		3	22.2	97.5	4.07
		Av	17.2	77.2	2.91
AG-27	Parent, 90° from weld	1	5.0	49.2	0.58
		2	13.5	70.5	4.46
		3	16.2	64.5	2.44
		Av	11.5	61.4	2.49
AG-35	Parent, 90° from weld	1	15.0	59.4	3.72
		2	2.7	38.9	0.26
		3	18.9	106.7	7.59
		Av	12.2	68.3	3.86
AG-43	Parent, 90° from weld	1	6.9	30.3	0.93
		2	10.4	25.3	1.86
		3	8.1	59.6	2.21
		Av	8.5	38.4	1.67
AG-52	Parent, 180° from weld	1	12.7	81.2	6.34
		2	8.8	85.4	4.63
		3	3.1	37.3	0.22
		Av	8.2	67.9	3.73
AG-60	Parent, 180° from weld	1	9.7	68.7	1.93
		2	17.0	93.3	3.33
		3	3.1	47.5	0.25
		Av	9.9	69.8	1.84
AG-68	Parent, 180° from weld	1	8.5	67.5	1.04
		2	17.3	80.3	2.88
		3	1.9	35.5	0.14
		Av	9.2	61.1	1.35

Table 22. SWC ratios in tests in H_2S-saturated NACE solution on pipe CA.

Coupon No.	Location in pipe	Section No.	% CTR	% CLR	% CSR
CA-16W	Across weld	1	19.4	55.8	2.88
		2	18.7	49.8	2.28
		3	11.9	50.7	1.78
		Av	16.6	52.1	2.31
CA-20W	Across weld	1	18.6	51.2	2.44
		2	18.4	74.2	2.78
		3	21.2	49.0	2.42
		Av	19.4	58.2	2.55
CA-25W	Across weld	1	22.0	84.4	1.88
		2	37.0	98.3	6.55
		3	9.2	50.7	0.53
		Av	22.7	77.8	2.99
CA-33	Parent, 90° from weld	1	10.1	40.8	1.99
		2	11.1	45.8	1.90
		3	9.7	21.3	0.64
		Av	10.3	36.0	1.51
CA-41	Parent, 90° from weld	1	14.2	27.0	1.40
		2	19.0	56.0	2.34
		3	23.7	45.2	2.22
		Av	19.0	42.7	1.99
CA-49	Parent, 90° from weld	1	36.5	75.6	8.16
		2	8.7	26.6	4.85
		3	31.0	97.0	5.63
		Av	25.4	66.4	4.76
CA-58	Parent, 180° from weld	1	12.8	22.5	0.78
		2	7.8	23.5	0.86
		3	12.7	32.8	0.60
		Av	11.1	26.3	0.75
CA-66	Parent, 180° from weld	1	24.5	47.2	2.48
		2	31.1	58.4	3.47
		3	20.5	54.8	2.14
		Av	25.4	53.5	2.70
CA-74	Parent, 180° from weld	1	22.9	34.8	2.23
		2	24.5	77.9	1.62
		3	15.7	59.1	1.62
		Av	21.0	57.3	1.82

Table 23. SWC ratios in tests in H_2S-saturated NACE solution on pipe CB.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CB-2W	Across weld	1	29.9	66.7	4.67
		2	16.4	41.3	2.32
		3	59.1	99.8	11.56
		Av	35.1	69.2	6.18
CB-6W	Across weld	1	19.6	31.8	1.95
		2	24.6	52.5	5.11
		3	31.7	85.8	11.15
		Av	25.3	56.7	6.07
CB-11W	Across weld	1	29.5	105.1	9.45
		2	0	0	0
		3	41.0	72.3	7.87
		Av	23.5	59.1	5.77
CB-27	Parent, 90° from weld	1	21.8	106.8	18.52
		2	47.1	111.0	11.19
		3	46.4	134.2	10.48
		Av	38.5	117.3	13.40
CB-35	Parent, 90° from weld	1	52.2	131.7	24.60
		2	40.2	128.8	11.03
		3	25.8	81.6	5.72
		Av	39.4	114.0	13.78
CB-43	Parent, 90° from weld	1	39.2	119.5	8.25
		2	39.6	105.7	13.03
		3	20.7	70.1	2.75
		Av	33.2	98.4	8.01
CB-52	Parent, 180° from weld	1	30.3	134.4	17.72
		2	22.0	81.3	6.59
		3	23.3	75.3	8.10
		Av	25.2	97.0	10.80
CB-60	Parent, 180° from weld	1	14.9	94.0	2.99
		2	16.4	77.6	2.15
		3	21.2	99.0	3.00
		Av	17.5	90.2	2.71
CB-68	Parent, 180° from weld	1	25.4	97.3	2.45
		2	38.0	162.1	15.22
		3	52.2	166.4	23.90
		Av	38.5	141.9	13.86

Table 24. SWC ratios in tests in H_2S-saturated NACE solution on pipe CC.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CC-2W	Across weld	1	7.7	40.5	0.50
		2	14.2	34.9	2.95
		3	2.5	8.6	0.14
		Av	8.1	27.9	1.19
CC-6W	Across weld	1	21.9	54.9	1.04
		2	38.9	51.3	2.51
		3	13.0	49.4	1.25
		Av	24.6	51.9	1.60
CC-11W	Across weld	1	21.3	64.9	3.01
		2	5.6	9.6	0.11
		3	16.9	80.3	1.94
		Av	14.6	51.6	1.69
CC-27	Parent, 90° from weld	1	10.4	60.5	3.21
		2	11.2	91.0	0.96
		3	10.9	55.0	1.63
		Av	10.9	68.8	1.93
C-35	Parent, 90° from weld	1	20.5	60.7	2.80
		2	5.9	52.6	0.72
		3	14.1	71.8	1.74
		Av	13.5	61.7	1.75
CC-43	Parent, 90° from weld	1	6.1	41.4	0.68
		2	9.6	92.3	1.60
		3	6.5	35.9	1.92
		Av	7.4	56.5	1.39
CC-52	Parent, 180° from weld	1	16.4	155.2	1.69
		2	1.6	7.7	0.05
		3	5.7	49.4	0.28
		Av	7.9	70.8	0.67
CC-60	Parent, 180° from weld	1	7.6	118.9	1.49
		2	6.4	162.7	2.13
		3	4.1	26.9	0.28
		Av	6.0	102.8	1.30
CC-68	Parent, 180° from weld	1	1.6	24.6	0.15
		2	5.7	62.2	0.58
		3	5.2	138.5	1.29
		Av	4.2	75.1	0.67

Table 25. SWC ratios in tests in H_2S-saturated NACE solution on pipe CD.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CD-2W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CD-6W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CD-11W	Across weld	1	3.1	2.0	0.06
		2	0	0	0
		3	0	0	0
		Av	1.0	0.7	0.02
CD-27	Parent, 90° from weld	1	1.2	2.0	0.02
		2	2.3	1.5	0.04
		3	4.1	4.8	0.07
		Av	2.5	2.8	0.04
CD-35	Parent, 90° from weld	1	4.7	38.3	0.88
		2	5.3	13.1	0.49
		3	5.3	13.6	0.20
		Av	5.1	21.7	0.52
CD-43	Parent, 90° from weld	1	1.2	1.0	0.01
		2	1.2	1.7	0.02
		3	1.8	3.0	0.02
		Av	1.4	1.9	0.02
CD-52	Parent, 180° from weld	1	3.5	9.9	0.13
		2	4.7	15.9	0.53
		3	2.9	13.6	0.09
		Av	3.7	13.2	0.25
CD-60	Parent, 180° from weld	1	1.8	2.0	0.02
		2	1.2	5.1	0.03
		3	2.3	1.0	0.02
		Av	1.8	2.7	0.02
CD-68	Parent, 180° from weld	1	11.6	37.7	2.75
		2	26.2	42.7	11.17
		3	15.1	42.2	4.12
		Av	17.6	40.8	6.01

Table 26. SWC ratios in tests in H_2S-saturated NACE solution on pipe CE.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
CE-2W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-6W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-11W	Across weld	1	0	0	0
		2	0	0	0
		3	0	0	0
		Av	0	0	0
CE-27	Parent, 90° from weld	1	1.1	8.5	0.06
		2	0.4	3.5	0.01
		3	2.2	21.8	0.10
		Av	1.2	11.2	0.06
CE-35	Parent, 90° from weld	1	0.7	1.5	0.01
		2	0.4	1.5	0.01
		3	1.1	1.0	0.01
		Av	0.7	1.3	0.01
CE-43	Parent, 90° from weld	1	0	0	0
		2	0.7	4.7	0.02
		3	2.2	15.7	0.06
		Av	1.0	6.8	0.03
CE-52	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	1.8	1.7	0.03
		Av	0.6	0.6	0.01
CE-60	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	0.7	1.5	0.01
		Av	0.2	0.5	<0.01
CE-68	Parent, 180° from weld	1	0	0	0
		2	0	0	0
		3	1.8	12.0	0.05
		Av	0.6	4.0	0.02

Table 27. SWC ratios in tests in H_2S-saturated NACE solution on pipe Z.

Coupon No.	Location in pipe	Section No.	%		
			CTR	CLR	CSR
Z-2W	Across weld	1	0	0	0
		2	1.2	7.4	0.09
		3	8.0	54.0	1.66
		Av	3.1	20.5	0.58
Z-6W	Across weld	1	11.4	46.0	1.38
		2	0.4	3.2	0.01
		3	0	0	0
		Av	3.9	16.4	0.46
Z-11W	Across weld	1	0	0	0
		2	1.2	3.6	0.04
		3	3.2	13.9	0.44
		Av	1.5	5.8	0.16
Z-27	Parent, 90° from weld	1	5.6	18.9	0.16
		2	21.3	59.9	5.12
		3	12.7	92.8	8.02
		Av	13.2	57.2	4.43
Z-35	Parent, 90° from weld	1	4.4	47.9	0.73
		2	0.4	9.7	0.04
		3	22.9	90.6	2.84
		Av	9.2	49.4	1.20
Z-43	Parent, 90° from weld	1	15.5	43.1	2.15
		2	6.3	69.6	3.26
		3	17.6	93.0	5.19
		Av	13.1	68.6	3.53
Z-52	Parent, 180° from weld	1	7.5	42.9	1.15
		2	34.3	80.3	5.53
		3	13.0	67.4	2.76
		Av	18.3	63.5	3.15
Z-60	Parent, 180° from weld	1	24.1	48.5	5.07
		2	39.3	121.4	10.93
		3	9.1	45.7	0.57
		Av	24.2	71.9	5.52
Z-68	Parent, 180° from weld	1	24.5	114.6	4.79
		2	39.4	118.9	14.03
		3	23.0	78.6	5.48
		Av	29.0	104.0	8.10

Table 28. Average values in triplicate tests of crack thickness ratio (CTR, %).

Pipe	Synthetic seawater (B.P.)			Acidified NaCl (NACE)		
	W	90°	180°	W	90°	180°
AB	4.7	2.4	2.3	24	23	21
AE	4.9	8.2	7.5	12	19	14
AG	7.0	0.1	0.7	15	11	9.1
CA	5.0	6.8	13	20	18	19
CB	0.9	9.8	17	28	37	27
CC	0.2	1.8	3.0	16	11	6
CD	0	0	0	0.3	3.0	7.7
CE	0	0	0.2	0	1.0	0.5
Z	0	5.3	3.9	2.8	12	24

Table 29. Average values in triplicate tests of crack length ratio (CLR, %).

Pipe	Synthetic seawater (B.P.)			Acidified NaCl (NACE)		
	W	90°	180°	W	90°	180°
AB	19	5.4	7.0	68	71	60
AE	24	63	71	50	134	133
AG	26	0.6	3.5	73	56	66
CA	20	26	40	63	48	46
CB	1.3	45	85	62	110	110
CC	3.7	5.8	21	44	62	83
CD	0	0	0	0.2	8.8	19
CE	0	0	1.2	0	6.4	1.7
Z	0	30	26	14	58	80

Table 30. Average values in triplicate tests of crack sensitivity ratio (CSR, %).

Pipe	Synthetic seawater (B.P.)			Acidified NaCl (NACE)		
	W	90°	180°	W	90°	180°
AB	0.56	0.22	0.29	4.1	4.3	2.5
AE	0.61	1.5	2.3	1.7	6.1	3.2
AG	0.74	<0.01	0.12	2.7	2.7	2.3
CA	0.36	1.3	1.8	2.6	2.8	1.8
CB	0.06	2.8	4.6	6.0	11.7	9.1
CC	0.04	0.07	0.28	1.5	1.7	0.88
CD	0	0	0	<0.01	0.19	2.1
CE	0	0	0.03	0	0.03	0.01
Z	0	0.63	0.75	0.40	3.1	5.6

Table 31. Average SWC ratios in different microstructural zones of weld coupons tested in synthetic seawater.

Pipe	Heat-affected zone			Parent, 0° from weld		
	CTR, %	CLR, %	CSR, %	CTR, %	CLR, %	CSR, %
AB	11	33	0.26	5.2	32	0.80
AE	4.5	16	0.21	6.2	31	0.84
AG	11	18	0.90	7.6	34	0.91
CA	10	29	0.63	6.0	26	0.43
CB	0	0	0	1.4	2.0	0.10
CC	0	0	0	0.3	5.5	0.06
CD	0	0	0	0	0	0
CE	0	0	0	0	0	0
Z	0(1)	0(1)	0(1)	0	0	0

(1) SSC in coarse-grained HAZ

Table 32. Average SWC ratios in different microstructural zones of weld coupons tested in the NACE solution.

Pipe	Heat-affected zone			Parent, 0° from weld		
	CTR, %	CLR, %	CSR, %	CTR, %	CLR, %	CSR, %
AB	66	97	7.02	25	75	4.60
AE	16(1,2)	42(1,2)	2.78(1,2)	12	63	1.55
AG	18(1)	49(1)	1.39(1)	18	96	3.53
CA	88	221	12.11	17	57	1.99
CB	26	65	5.58	35	77	7.78
CC	15(2)	65(2)	1.89(2)	14	50	1.31
CD	0	0	0	0.5	0.3	0.01
CE	0	0	0	0	0	0
Z	0	0	0	7.5	38	1.16

(1) SSC in coarse-grained HAZ

(2) SSC in weld fusion zone

Table 33. Distribution of SWC through the pipe wall thickness in parent metal.

Pipe	In B.P. solution		In NACE solution	
	% Central(1)	% Surface(2)	% Central	% Surface
AB	20	80	9	91
AE	83	17	75	25
AG	96	4	72	28
CA	8	92	9	91
CB	98	2	97	3
CC	21	79	58	42
CD	- no cracks -		90	10
CE	0	100(3)	84	16
Z	94	6	87	13

(1) Between 1/4 and 3/4 through wall thickness

(2) Within 1/4 of wall thickness from surface

(3) Only 1 small crack

Table 34. Tukon microhardness (500 g) measurements expressed in Rockwell hardness units.

Pipe	Parent	Weld HAZ		Weld fusion zone
		Fine-grained	Coarse-grained	
AB	HRB 95.5, 97, 97.5	HRB 93.5, 95, 96, 96.5, 96.5, 96.5, 97, 97, 98, 98.5	HRB 94, 95, 97, 97, 98, 98.5, 99	HRB 96.5, 99
AE	HRB 94.5, 94.5, 94.5 94.5, 95.5, 97	HRB 97, 98, 98, 100, 100; HRC 24, 25.5	HRC 25, 25.5, 26, 26, 26.5, 27, 27	HRB 98.5, 99.5, 99.5; HRC 25
AG	HRB 98, 99.5 HRC 24, 25.5	HRB 95, 96, 96.5, 96.5, 98.5, 99.5 HRC 24, 25, 25, 25, 25.5, 26	HRB 98, 99.5 HRC 23.5, 23.5, 29	HRB 99.5, 100
CA	HRB 85, 88, 89.5	HRB 88, 88, 88, 88.5 89, 91, 91, 94.5 96.5	HRB 90.5, 92, 92, 92, 93, 95	HRB 92.5, 93
CB	HRB 88, 91, 91.5, 92	HRB 89.5, 90, 91, 91.5, 92, 95, 96.5, 97	HRB 94, 95.5, 96, 97, 97.5 HRC 24	HRB 94, 95
CC	HRB 92, 92.5, 92.5, 94.5, 95.5, 96.5	HRB 95, 95, 95.5, 95.5, 96, 96.5, 96.5	HRB 94, 95, 95, 96, 96	HRB 96, 98
CD	HRB 89, 91.5, 92	HRB 88, 88.5, 89, 89.5, 89.5, 91, 91	HRB 85.5, 89.5, 94	HRB 90, 90
CE	HRB 86, 87.5, 87.5	HRB 84.5, 87.5, 87, 87, 88, 88, 89, 89	HRB 89.5, 90	HRB 95, 96.5
Z	HRB 99.5, 99.5 HRC 23.5	HRB 96.5, 96.5, 98.5, 98.5, 99, 99.5, 99.5, 99.5, 99.5	HRB 99, 99.5, 99.5 HRC 26.5, 29, 29.5, 29.5	HRB 99 HRC 25.5

Table 35. Determinations of "diffusible hydrogen at 45°C".

Pipe	Synthetic seawater (B.P.)			Acidified NaCl (NACE)		
	Coupon No.	CTR, %	Vol H_2 mL (STP) per 100 g	Coupon No.	CTR, %	Vol H_2 mL (STP) per 100 g
AB	-	-	-	AB-2W	27.5	4.45
	-	-	-	AB-27	29.1	4.55
	-	-	-	AB-52	26.4	4.50
AE	AE-1W	4.3	2.10	AE-2W	15.2	3.00
	AE-26	6.1	1.75	AE-27	18.1	4.30
	AE-51	8.2	1.80	AE-52	15.0	2.85
AG	AG-1W	7.1	1.75	AG-2W	11.4	3.45
	AG-26	0	0.95	AG-27	11.5	3.20
	AG-51	0	1.05	AG-52	8.2	2.65
CA	-	-	-	CA-2W	27	2.45
	-	-	-	CA-16W	16.6	2.25
	-	-	-	-	-	-
CB	-	-	-	CB-2W	35.1	4.55
	-	-	-	CB-27	38.5	4.85
	-	-	-	CB-52	25.2	2.85
CC	-	-	-	CC-2W	8.1	4.05
	-	-	-	CC-27	10.9	2.70
	-	-	-	CC-52	7.9	2.70
CD	CD-1W	0	1.10	CD-2W	0	4.30
	CD-26	0	1.70	CD-27	2.5	4.30
	CD-51	0	1.15	CD-52	3.7	4.60
CE	CE-1W	0	0.35	CE-2W	0	0.80
	CE-26	0	0.25	CE-27	1.2	1.05
	CE-51	0.7	0.10	CE-52	0.6	1.20
Z	-	-	-	Z-2W	3.1	2.00
	-	-	-	Z-27	13.2	2.25
	-	-	-	Z-52	18.3	2.95

Table 36. Percentage of coupon area showing SWC in ultrasonic C-scan examination, as determined by Quantimet 900 image analysing computer.

Coupon	Area %, SWC	Coupon	Area %, SWC
AB-W	4	CC-W	17
-90	<1	-90	7
-180	<1	-180	1.5
AE-W	34	CD-W	9*
-90	65	-90	9*
-180	77	-180	9*
AG-W	11	CE-W	<1
-90	<1	-90	<1
-180	13	-180	<1
CA-W	11	Z-W	8
-90	15	-90	40
-180	6	-180	41
CB-W	2		
-90	49		
-180	53		

*Indication of SWC is an artifact; correct value is <1%

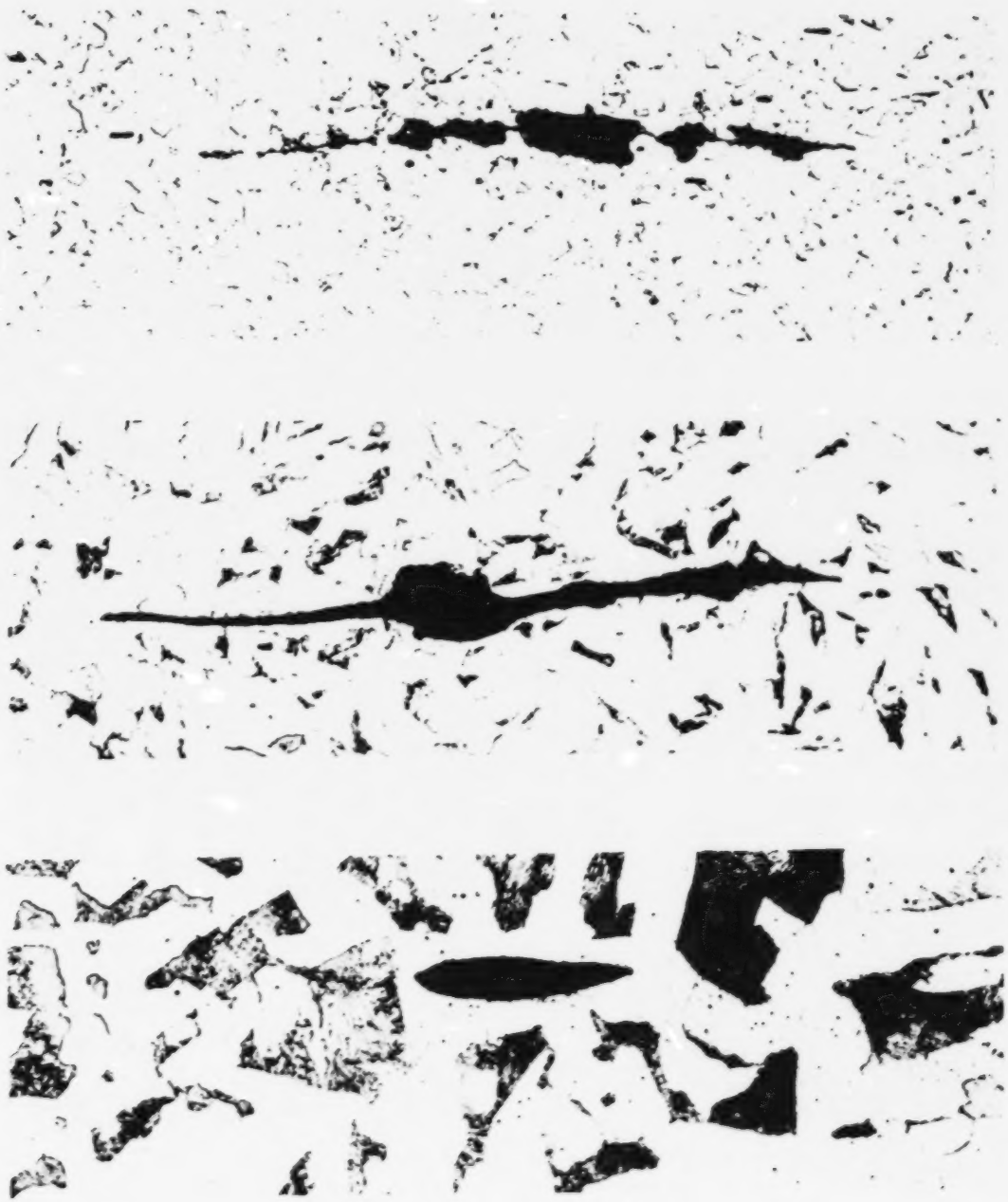


Fig. 1. Typical elongated inclusions observed near mill welds of as-received pipes AB, CA and CD in plane at right angles to rolling direction. X1000 (neg 6037, 6036, and 7997).

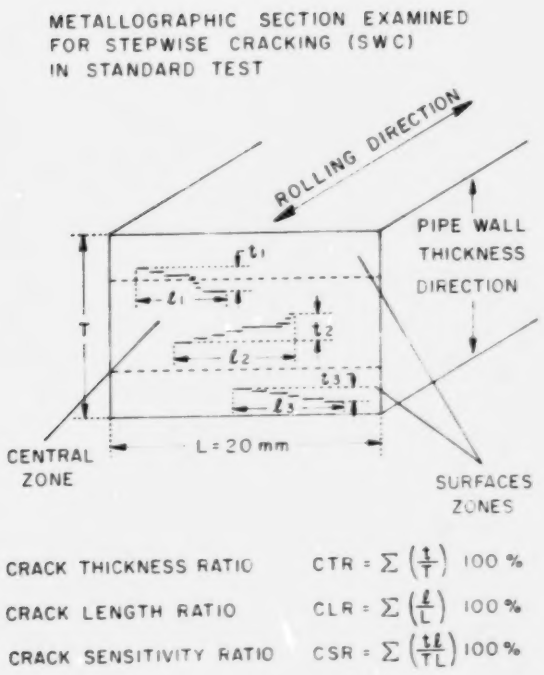


Fig. 2. Method used for the quantitative evaluation of SWC in metallographic sections of test coupons. (neg 7725)

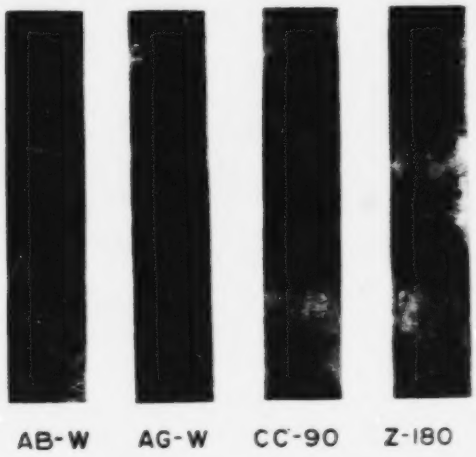
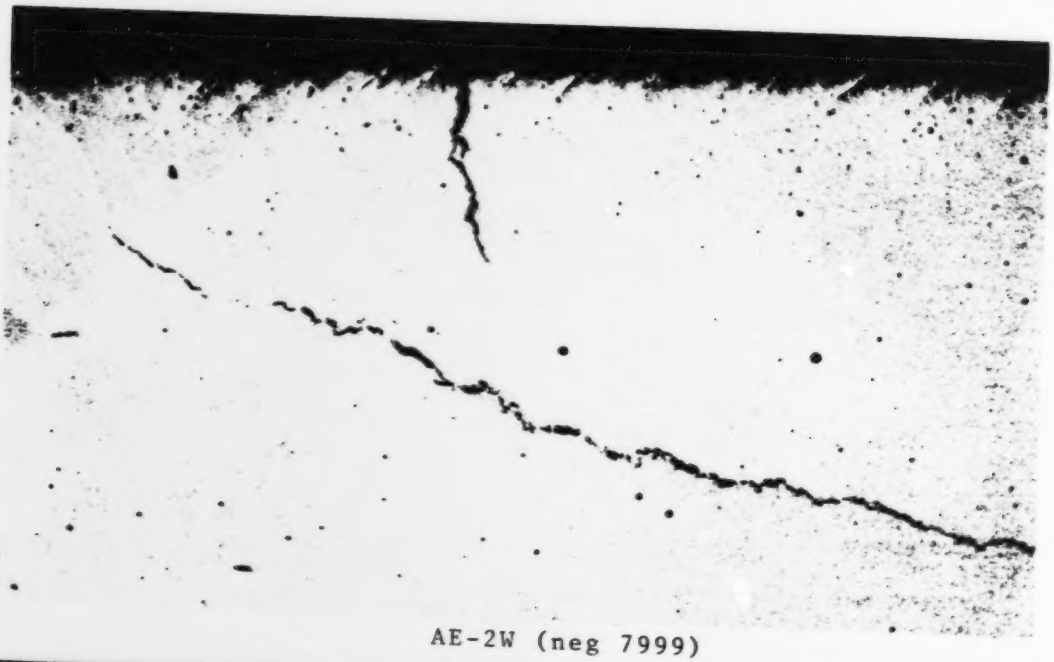
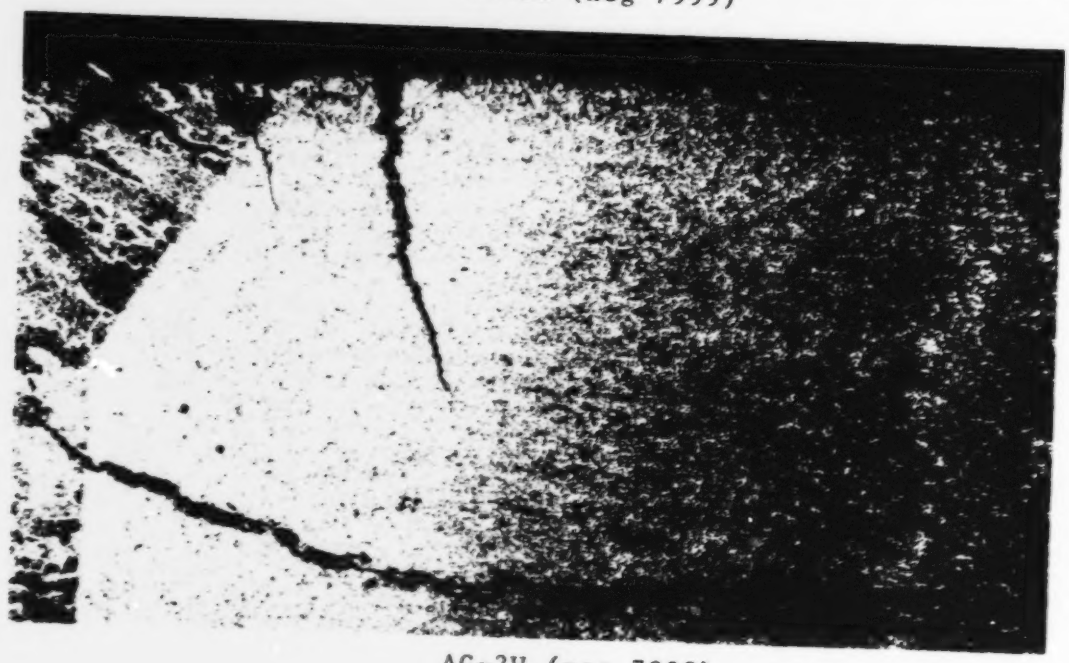


Fig. 3. Descaled SWC test coupons after immersion in H_2S-saturated NACE solution for 4 days showing "blistered" (at left) and "slightly blistered" surfaces. X0.56 (neg 7572)



AE-2W (neg 7999)



AG-2W (neg 7998)

Fig. 4. Examples of apparent sulphide stress cracking observed in the coarse-grained HAZ of coupons AE-2W and AG-2W; also in the weld fusion zone of AG-2W. X50

Fig. 5. Apparent sulphide stress cracking in the central portion of the weld fusion zone in coupon CC-6W. X50 (neg 8000)

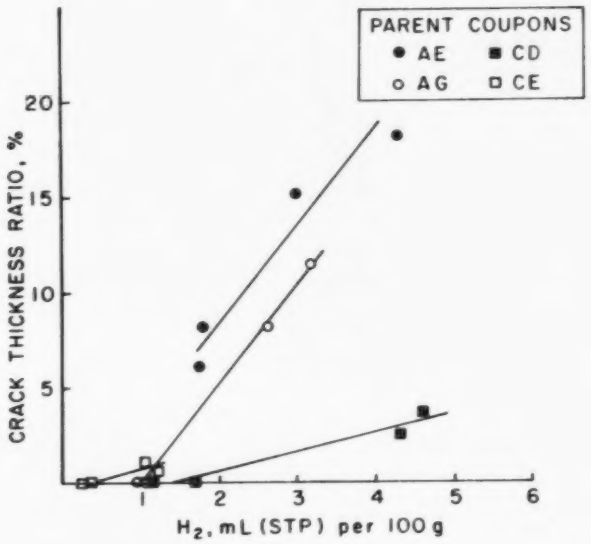


Fig. 6. Diffusible hydrogen at 45°C related to the crack thickness ratio for parent coupons of four pipes. (neg 7830)

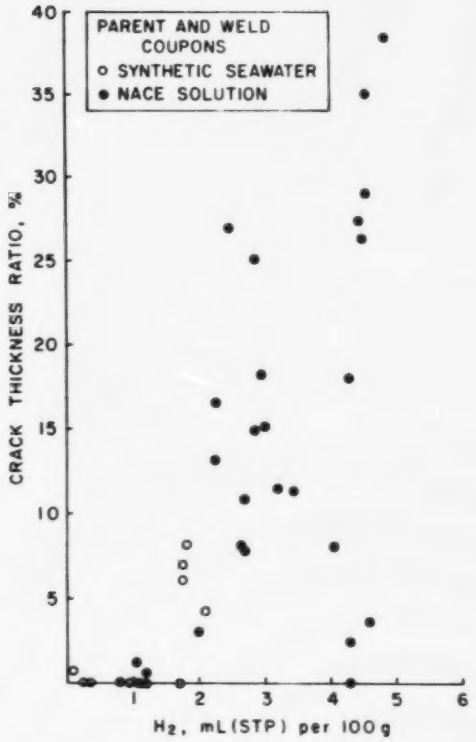


Fig. 7. Diffusible hydrogen at 45°C related to the crack thickness ratio for parent and weld coupons of nine pipes. (neg 7832)

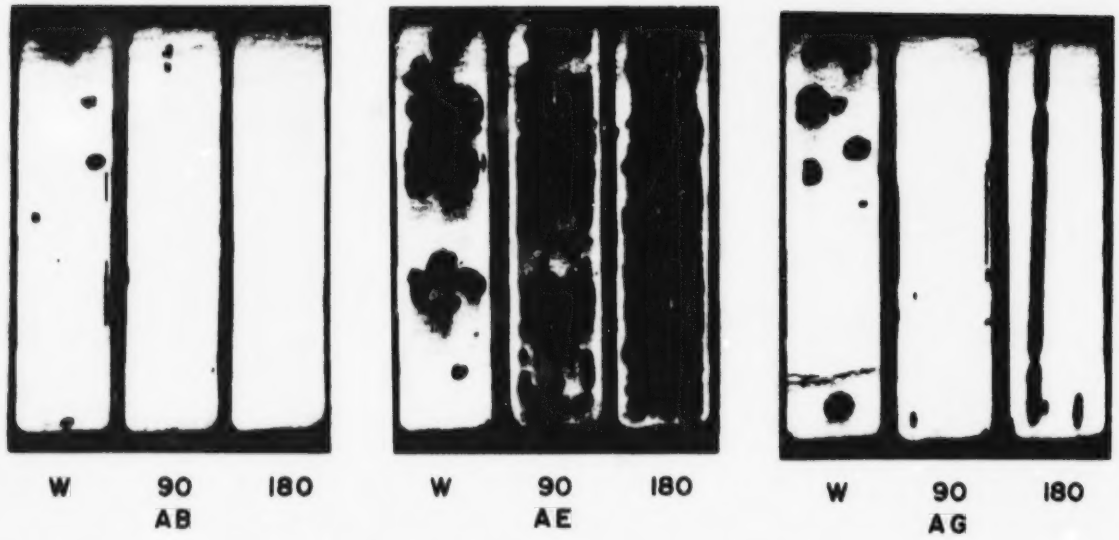


Fig. 8. Ultrasonic C-scan display of SWC damage in coupons of pipes AB, AE and AG, after immersion in H_2S-saturated synthetic seawater. X~0.6 (neg 7576 and 7574)

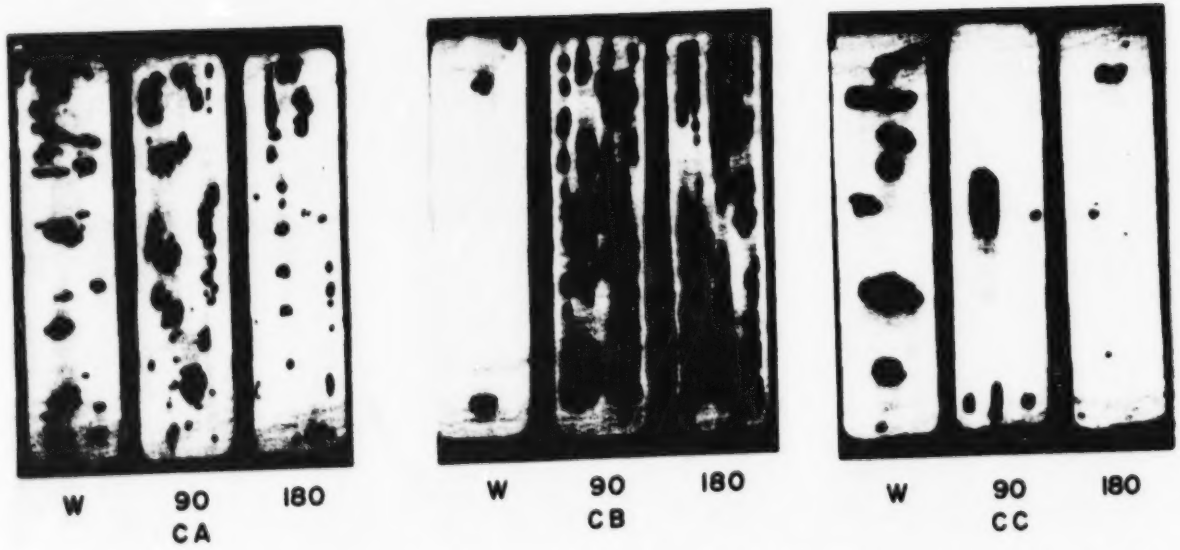


Fig. 9. Ultrasonic C-scan display of SWC damage in coupons of pipes CA, CB and CC, after immersion in H_2S-saturated synthetic seawater. X~0.6 (neg 7575 and 7577)

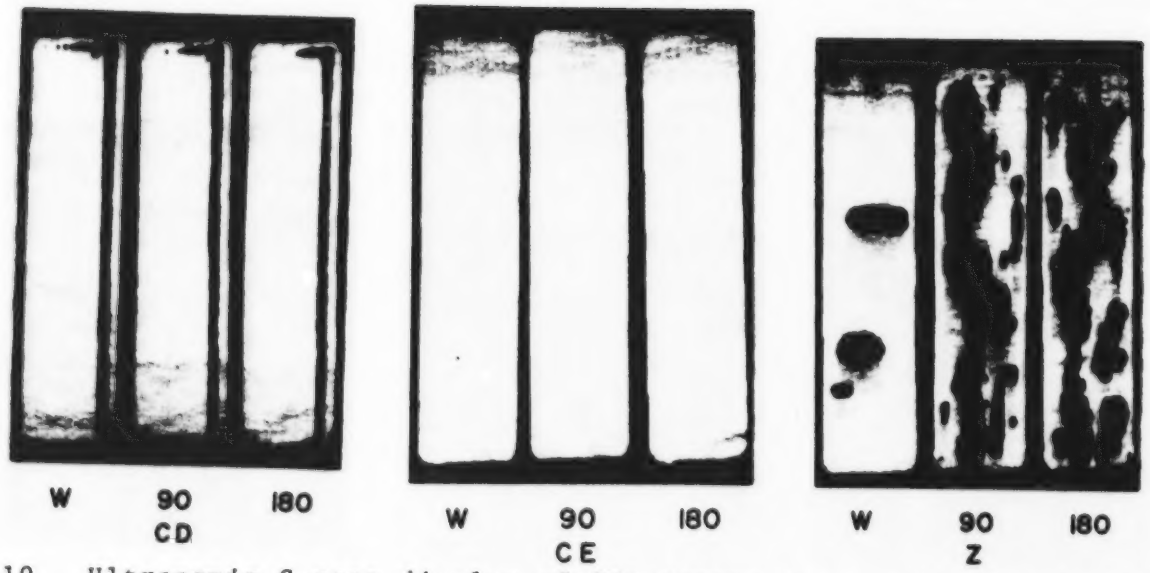


Fig. 10. Ultrasonic C-scan display of SWC damage in coupons of pipes CD, CE and Z, after immersion in H_2S-saturated synthetic seawater. X~0.6 (neg 7577, 7573 and 7576)

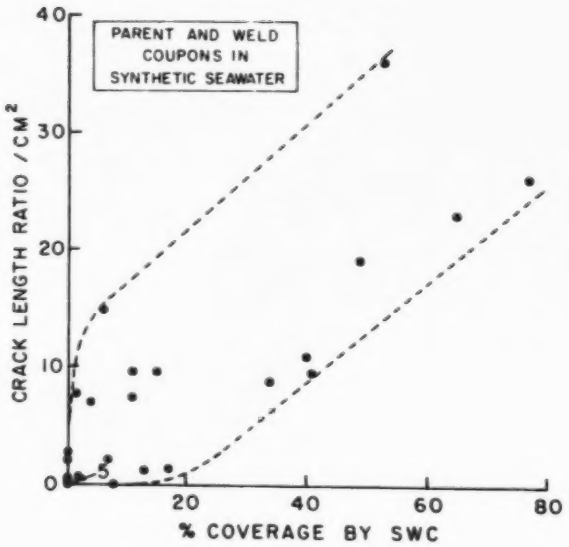


Fig. 11. Percentage coverage of test coupons by SWC as determined by ultrasonic C-scan, related to %CLR/cm^2. (neg 7904)